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Structure–activity relationship studies of SETD8 inhibitors†‡

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SETD8 (also known as SET8, PR-SET7, or KMT5A (lysine methyltransferase 5A)) is the only known lysine methyltransferase that catalyzes the monomethylation of histone H4 lysine 20 (H4K20). In addition to H4K20, SETD8 monomethylates non-histone substrates such as the tumor suppressor p53 and the proliferating cell nuclear antigen (PCNA). Because of its role in regulating diverse biological processes, SETD8 has been pursued as a potential therapeutic target. We recently reported the first substrate-competitive SETD8 inhibitor, UNC0379 (**1**), which is selective for SETD8 over 15 other methyltransferases. We characterized this inhibitor in a battery of biochemical and biophysical assays. Here we describe our comprehensive structure–activity relationship (SAR) studies of this chemical series. In addition to 2- and 4-substituents, we extensively explored 6- and 7-substituents of the quinazoline scaffold. These SAR studies led to the discovery of several new compounds, which displayed similar potencies as compound **1** and interesting SAR trends.

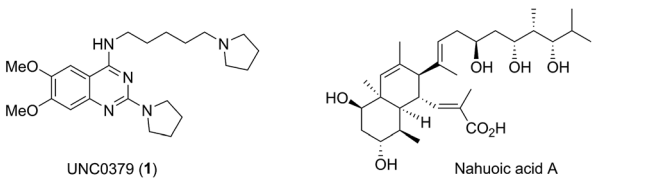
Introduction

Post-translational modifications (PTMs) of histones are critical in regulating gene expression and transcription.[1–3] Among a myriad of PTMs, histone lysine methylation has been recognized as a major mechanism in chromatin regulation. Histone lysine methylation typically takes place at the N-terminal tails of core histone proteins (H3, H4, H2A, and H2B) and is catalyzed by protein lysine methyltransferases (PKMTs). It is worth noting that PKMTs also methylate many non-histone substrates.[4]

PKMTs have been increasingly recognized as a class of potential therapeutic targets by the medicinal chemistry and drug discovery community. Consequently, a number of selective inhibitors of PKMTs have been discovered during recent years.[5–31] Related to PKMTs, protein arginine methyltransferases (PRMTs) catalyze the methylation of arginine residues of histone and non-histone proteins.[32] A number of selective inhibitors of PRMTs have also been reported.[33–35]

SETD8 (also known as SET8, PR-SET7, or KMT5A (lysine methyltransferase 5A)), first characterized in 2002, is the only known PKMT that catalyzes the monomethylation of histone H4 lysine 20 (H4K20).[36–38] Monomethylation of H4K20 (H4K20me) and SETD8 has been implicated in DNA damage response and cell cycle progression.[38] In addition, SETD8 promotes epithelial–mesenchymal transition (EMT) by physically associating with TWIST, a master regulator of EMT.[39] SETD8 also monomethylates lysine 382 (K382) of the tumor suppressor p53 and lysine 248 (K248) of the proliferating cell nuclear antigen (PCNA) and plays a potential role in human carcinogenesis.[40,41]

We recently reported UNC0379 (**1**) as the first substrate-competitive small-molecule inhibitor of SETD8 (Fig. 1).[42] Compound **1** is active in multiple biochemical (*e.g.*, radioactive methyl transfer and microfluidic capillary electrophoresis) and biophysical (*e.g.*, isothermal titration calorimetry and surface plasmon resonance) assays, and importantly, selective for SETD8 over 15 other methyltransferases.[42] The only other known selective inhibitor of SETD8 is a marine natural product nahuoic acid A, which is competitive with the co-factor *S*-adenosyl-L-methionine (SAM) (Fig. 1).[21] In this article, we describe



UNC0379 (**1**) — Nahuoic acid A

SETD8: IC_{50} = 7.3 ± 1.0 μM
Competitive with substrate
Selective over 15 other methyltransferases

SETD8: IC_{50} = 6.5 ± 0.5 μM
Competitive with the cofactor SAM

Fig. 1 Structures of the known selective inhibitors of SETD8.

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our comprehensive structure–activity relationship (SAR) studies of the quinazoline template represented by compound **1**, which resulted in the discovery of interesting SAR trends and novel analogs with similar potencies as compound **1**.

Results and discussion

Our strategy for studying the SAR of the UNC0379 series was to extensively explore the 2-, 4-, 6-, and 7-substituents (Fig. 2). We previously reported the initial SAR results of the 2- and 4-substituents.[42] In these new studies, we investigated not only additional 2- and 4-substituents, but also 6- and 7-substituents, the two regions that have not been previously explored for SETD8.

We first explored the 4-amino moiety of the quinazoline scaffold. Compounds **1–15** (Scheme 1 and Table 1) were synthesized from commercially available 2,4-dichloro-6,7-dimethoxyquinazoline and corresponding amines in good yields. As previously reported,[6] we displaced the 4-chloro group with the first set of amines at room temperature. The 2-chloro group was substituted by the second set of amines under microwave heating conditions, yielding the desired 2,4-diamino-6,7-dimethoxyquinazolines (Scheme 1).

The ring size of the terminal cyclic amino group did not have a significant impact on SETD8 potency (Table 1). Pyrrolidine (compound **1**), piperidine (compound **2**), and azepane (compound **3**) resulted in similar potencies. The replacement of the cyclic amino group with an acyclic amino group such as the dimethyl amine group (compound **4**) did not lead to a significant potency change either. However, increasing the length of the side chain from 5 to 6 carbons (compound **4** *versus* compound **5**) resulted in a decrease in potency. We previously reported that decreasing the length of the side chain also led to a decrease in potency.[42] Interestingly, replacing the dimethyl amine group with the primary amino group slightly decreased the potency (compound **5** *versus* compound **6**). We next explored various conformation-constrained analogs and found that these compounds (**7–10**) were not as potent as compound **1**. In addition to exploring the length of the side chain, we also attempted to replace the straight 5-carbon chain with several amide-containing linkers and found that amide **11** was significantly less potent than compound **1** and amide **12** was completely inactive. We previously reported that compound **13** was weakly active against SETD8.[42] Consistent with the results

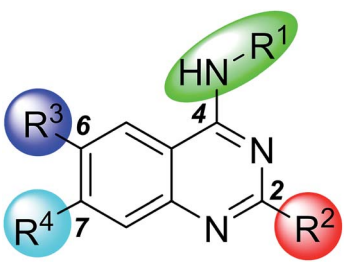
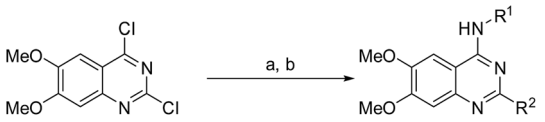


Fig. 2 The four highlighted regions were explored for studying the SAR of the UNC0379 series.



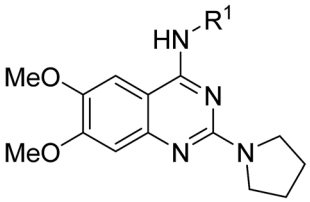
Scheme 1 Typical synthesis of 2,4-diamino-6,7-dimethoxyquinazolines. Reagents and conditions: (a) R^1 amines, THF, *N*,*N*-diisopropylethylamine, room temperature; (b) R^2 amines, *n*-BuOH, DIPEA, microwave, heat.

of amide **12**, amides **14** and **15** did not display any activity against SETD8. Taken together, these results suggest that: (1) the terminal pyrrolidine group can be modified without potency loss and (2) the 5-carbon linker is optimal. In addition, we previously demonstrated that the basicity of the pyrrolidine nitrogen was important for maintaining potency for SETD8.[42]

We next investigated various 2-substituents at the quinazoline core (Scheme 2 and Table 2). Synthesis of compounds **16–18** was described previously.[42] Compounds **20–25** were prepared according to the synthesis route illustrated in Scheme 1. Buchwald–Hartwig amination reaction conditions[43] were used to synthesize compounds **19** and **26–32** from the known intermediate 2-chloro-6,7-dimethoxy-*N*-(5-(pyrrolidin-1-yl)pentyl)quinazolin-4-amine[42] and commercially available amines (Scheme 2). Compounds **19** and **26–32** could not be generated using standard nucleophilic conditions (Scheme 1) in good yields. A Suzuki coupling reaction[44] was used to prepare compounds **33–36** from the same intermediate and commercially available aromatic boronic acids (Scheme 2).

As shown in Table 2, replacing the pyrrolidine (compound **1**) with either piperidine (compound **16**) or azepane (compound **17**) resulted in a significant loss of potency, suggesting that a larger group is disfavored. On the other hand, the replacement of the pyrrolidine (compound **1**) with the dimethyl amine group (compound **18**) did not lead to a significant potency change. These results were reported previously.[42] Interestingly, the 3,3-difluoroazetidine (compound **19**) resulted in a large loss of potency, possibly due to the increase of the compound's polarity. We attempted to synthesize a simple azetidine analog, but found that the target molecule was unstable and could not be isolated. Adding a methyl substituent to the pyrrolidine (compound **20**) led to about two-fold drop in potency. We previously reported that compound **21** displayed some activity for SETD8.[42] Based on this result, we attempted to introduce a pyrrolidine with a 2–5-carbon linker and were disappointed to find that these compounds (**22–25**) did not exhibit any activity for SETD8. We also explored unsubstituted and substituted *N*-methylanilines and anilines. As shown in Table 2, unsubstituted *N*-methylaniline (compound **26**) and *N*-methylaniline with either an electron-donating group (methoxy, compound **27**) or an electron-withdrawing group (nitro, compound **28**) at the *para*-position were inactive. Similarly, unsubstituted aniline (compound **29**) and anilines with either an electron-donating group (compound **30**) or an electron-withdrawing group (compounds **31** and **32**) at the *para*-position did not display any activity. Finally, we attempted to replace the pyrrolidine with a phenyl or substituted phenyl group containing an

Table 1 SAR of the 4-amino moiety



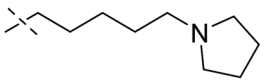
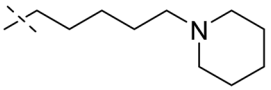
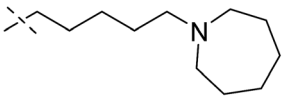
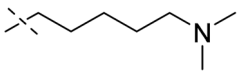
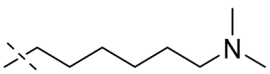
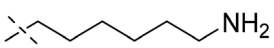
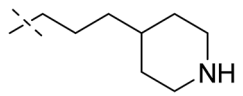
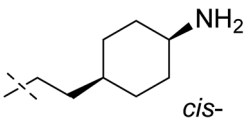
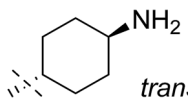
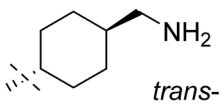
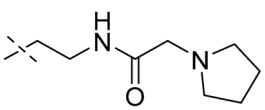
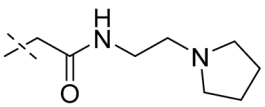
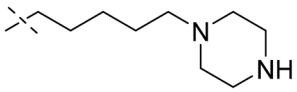
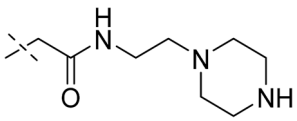
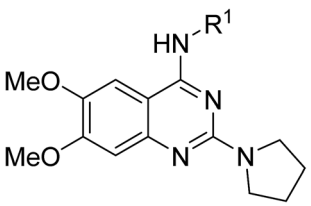
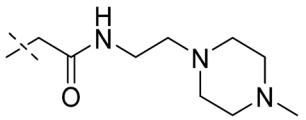
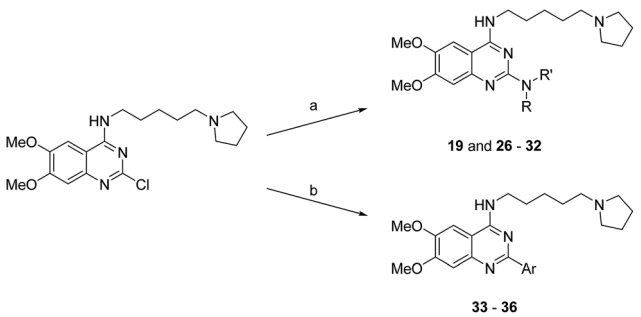
Compound	R^1 group	SETD8 IC_{50}[a] (μM)
1		7.3 ± 1.0[b]
2		7.9 ± 0.8[b]
3		7.9 ± 1.2
4		7.9 ± 1.4[b]
5		26 ± 5
6		40 ± 1
7		40 ± 6
8	 cis-	43 ± 5
9	 trans-	>250
10	 trans-	>250
11		63 ± 19
12		>250
13		32 ± 8[b]
14		>250

Table 1 (*Contd.*)



Compound	R^1 group	SETD8 IC_{50}[a] (μM)
15		>250

[a] IC_{50} determination experiments were performed in duplicate. [b] IC_{50} value was reported previously.[42]



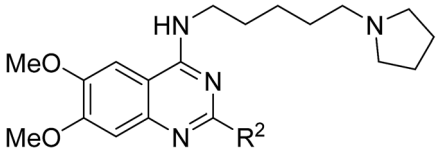
Scheme 2 Synthesis of compounds **19** and **26–36**. Reagents and conditions: (a) amines, $Pd(OAc)_2$, (+)-BINAP, Cs_2CO_3, THF, microwave, heat; (b) aromatic boronic acid, $Pd(PPh_3)_4$, K_2CO_3, dioxane–water, microwave, heat. Ar, aromatic ring.

electron-donating or an electron-withdrawing group at the *para*-position, but found that none of these compounds (**33–36**) were active against SETD8. Taken together, these results suggest that the SAR at the 2-substituent is very tight. The vast majority of the modifications we made led to a significant or complete loss of potency for SETD8.

We also extensively explored the 6- and 7-substituents (Scheme 3 and Table 3), which were not studied previously. Compounds **37–45** were prepared from different 6,7-substituted 2,4-dichloroquinazolines (synthesis of these intermediates is detailed in the ESI‡) according to the synthesis route illustrated in Scheme 1. Synthesis of compounds **46–49** is outlined in Scheme 3. Briefly, debenzylation of compound **45** *via* hydrogenation produced compound **46**. Nucleophilic substitution reactions between phenol **46** and various alkyl bromides afforded compounds **47–50**.

We found that the removal of both methoxy groups (compound **37**) or the 6-methoxy group (compound **38**) completely abolished activity (Table 3). Interestingly, the removal of the 7-methoxy group (compound **39**) led to about 7-

Table 2 SAR of the 2-substituted group



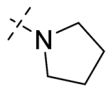
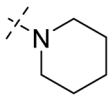
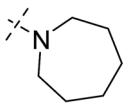
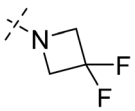
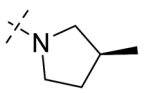
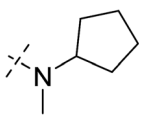
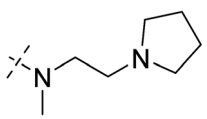
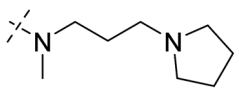
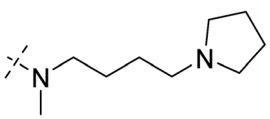
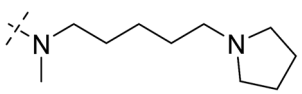
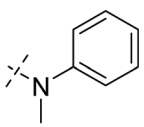
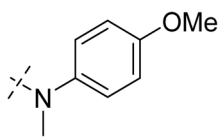
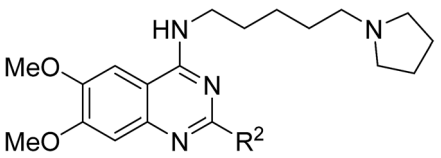
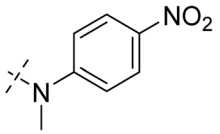
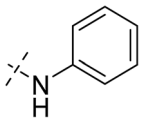
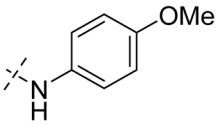
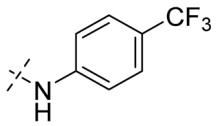
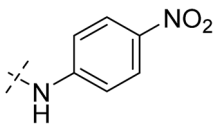
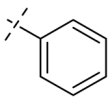
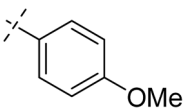
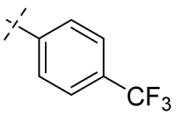
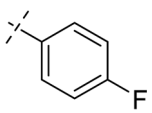
Compound	R^2 group	SETD8 IC_{50}[a] (μM)
1		7.3 ± 1.0[b]
16		94 ± 18[b]
17		>250[b]
18		9.2 ± 1.2[b]
19		110 ± 4
20		15 ± 3
21		37 ± 9[b]
22		>250
23		>250
24		>250
25		>250
26		>250
27		>250

Table 2 (*Contd.*)

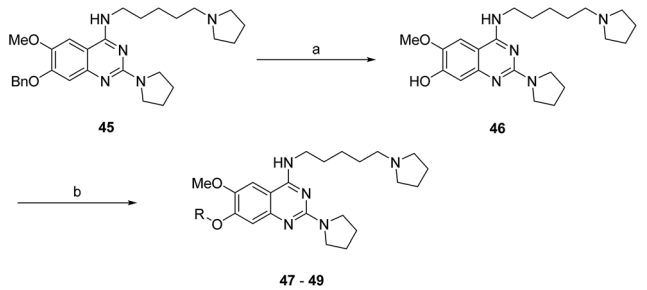


Compound	R^2 group	SETD8 IC_{50}[a] (μM)
28		>250
29		>250
30		>250
31		>250
32		>250
33		>250
34		>250
35		>250
36		>250

[a] IC_{50} determination experiments were performed in duplicate. [b] IC_{50} value was reported previously.[42]

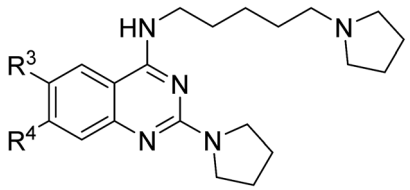
fold loss in potency, but it retained some activity against SETD8. These results suggest that the 6-methoxy group may be more important for maintaining SETD8 potency compared with the 7-methoxy group.

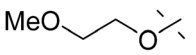
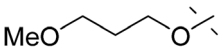
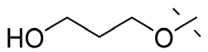
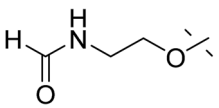
We next investigated several 6-substituents while holding the 7-methoxy group constant and found that the replacement of



Scheme 3 Synthesis of compounds **46–49**. Reagents and conditions: (a) H_2, Pd/C, EtOH, room temperature; (b) RBr, K_2CO_3, DMF, room temperature.

Table 3 SAR of the 6- and 7-substituted groups



Compound	R^3 group	R^4 group	SETD8 IC_{50}[a] (μM)
1	MeO–	MeO–	7.3 ± 1.0[b]
37	H–	H–	>250
38	H–	MeO–	>250
39	MeO–	H–	52 ± 11
40	EtO–	MeO–	9.5 ± 0.9
41	*i*-PrO–	MeO–	61 ± 12
42	Cl–	MeO–	46 ± 11
43	MeO–	EtO–	11 ± 1
44	MeO–	*i*-PrO–	48 ± 10
45	MeO–	BnO–	130 ± 44
46	MeO–	HO–	>250
47	MeO–		8.0 ± 0.8
48	MeO–		40 ± 12
49	MeO–		24 ± 3
50	MeO–		8.7 ± 0.4

[a] IC_{50} determination experiments were performed in duplicate. [b] IC_{50} value was reported previously.[42]

the 6-methoxy group with the 6-ethoxy group did not result in a significant change in potency (compound **1** *versus* compound **40**). On the other hand, the 6-isopropoxy group (compound **41**) and the 6-chloro group (compound **42**) led to about 8-fold and 6-fold loss in potency, respectively, suggesting that a larger group or a less electron-donating group is disfavored at this position.

Lastly, we explored various 7-substituents while holding the 6-methoxy group constant. Slightly increasing the size of the 7-methoxy group to the 7-ethoxy group (compound **43**) did not significantly change the potency. On the other hand, the larger 7-isopropoxy group (compound **44**) and the 7-benzyloxy group (compound **45**) led to more than 6-fold and 17-fold potency drops, respectively. Interestingly, the 7-hydroxy group (compound **46**) completely abolished activity against SETD8. We next studied whether a linear chain could be tolerated at the 7-position. We were pleased to find that compound **47**, which contains the 7-methoxyethyloxy group, was as potent as compound **1**. However, the 7-methoxypropoxy group (compound **48**) and the 7-hydroxypropoxy group (compound **49**) led to a significant decrease in potency. Interestingly, compound **50**, which contains the 7-formylaminoethyloxy group, retained the same potency as compounds **1** and **47**. Taken together, these results suggest that the 7-position is amenable to modifications and there may be an opportunity to create more potent inhibitors of SETD8 by further exploring this region.

Conclusions

We comprehensively studied the SAR of the quinazoline scaffold represented by UNC0379 (compound **1**), which was recently discovered as the first substrate-competitive inhibitor of SETD8. We found a number of interesting SAR trends. They include: (1) at the 4-position, the terminal pyrrolidine group can be modified without potency loss and the 5-carbon linker is optimal; (2) at the 2-position, modifications are generally not tolerated and pyrrolidine and dimethylamino groups are optimal; (3) at the 6-position, the methoxy and ethoxy groups are preferred and a larger group or a less electron-donating group is disfavored; and (4) at the 7-position, modifications can be well tolerated and further exploration of this region may result in more potent SETD8 inhibitors. These SAR studies also led to the discovery of several novel compounds (**3**, **40**, **43**, **47** and **50**), which exhibited similar potencies as compound **1**. During the revision of this paper, several novel inhibitors of SETD8 have been reported.[45]

Acknowledgements

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